Diesel Emissions Evaluation Program
DEEP

Technology Transfer Initiative
October 2001

Sampling for Diesel Particulate Matter in Mines

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104-05348/

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CANMET – Mining and Mineral Sciences Laboratories Report MMSL 01-052 (TR)

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Introduction

Diesel powered mining equipment has allowed the industry to achieve tremendous improvements in productivity over the past 30 to 50 years. The diesel engine is an economical source of power and diesel powered equipment is rugged, mobile and versatile.

On the negative side, the toxicity of some diesel exhaust gases is well documented. In addition, increasing evidence is becoming available about the potential ***carcinogenicity*** of the solid fraction of diesel exhaust known as ***diesel particulate matter (DPM).*** Sampling and monitoring of mine worker exposure to diesel particulate is important in order to help assess the risk associated with exposure. Pinpointing the sources of diesel particulate and their characterization is also achieved by sampling and can help in the control of emissions.

This document is intended for mine personnel who are responsible for diesel contaminant exposure monitoring of miners, diesel engine maintenance personnel, joint health and safety committee members and others with a stake in mining health and safety related to diesel exhaust exposure.

The report will provide a brief overview of the physical and chemical characteristics of DPM and some of the guidelines and regulation for exposure monitoring in the workplace. Issues related to personal and ***direct exhaust sampling*** in mines will also be discussed. A brief description will also be made of sampling protocols, instrumentation, analytical methods and a few basic principles of exposure database use and maintenance. To help make this report clearer, some expressions or key words are defined in the next section of the report. These words are shown in the text in ***bold italics***.

Glossary

Adsorb:

The attachment of a substance to a surface. In this case it can be said that organic vapours condense as liquids and are adsorbed onto the solid carbon particles that form the core of diesel particulate matter.

Carcinogen, carcinogenicity:

A substance capable of causing cancer. Carcinogenicity, therefore, is a characteristic of a cancer causing substance.

Diesel particulate matter (DPM):

The portion of diesel exhaust which is made up of solid carbon particles and the attached chemicals including organic chemicals such as polycyclic aromatic hydrocarbons (PAHs) and inorganics such as sulphate compounds.

Direct exhaust sampling:

Direct sampling of diesel exhaust contaminants in the tailpipe of a vehicle as opposed to sampling in air.

Electro-magnetic fields:

Waves of energy that move freely in air and are produced by electric motors or any process or place where significant electric currents are present.

Elemental carbon (EC):

The pure carbon particles that are the basic building blocks of diesel particulate.

Field blanks:

Filter cassettes, used in quality control, that are identical to those used for sampling dust, except that these are not used in sampling. They are brought to the sampling site, handled as the regular sample cassettes would be and are sent back for analysis. It is expected that these cassettes will show little, or no trace of

contamination, otherwise, the results from exposure measurement using the regular sampling cassettes could be questioned.

Impactor:

A component of the dust sampling train which is required by ***MSHA*** to remove particles larger than 0.9 ***micron*** in size from the air being sampled. Diesel particulate is, for the most part, less than 0.9 micron in size.

Interference:

In diesel sampling, carbon substances or compounds from sources other than diesel exhaust that may cause the result of analysis to be over- or underestimated.

Litres per minute (L/min.):

Measure of the rate of flow of a gas or a liquid. For example a pump that moves 60 litres of air in one hour (60 minutes), pumps at a flow rate of 1 litre per minute or 1 L/min.

Micron (μm):

Unit of measurement equal to one millionth of a metre. It is used to measure very small objects, including airborne dust or aerosols such as diesel particulate. Also written and abbreviated as μm.

Milligrams per cubic metre (mg/m³):

A measure of the airborne concentration of a substance. In the case of airborne DPM, the mass of diesel particulate in milligrams found in one cubic metre of sampled air (1000 litres) is used to calculate the concentration of DPM. If 0.34 milligrams of diesel particulate is measured in one cubic metre of air, then the concentration of DPM is 0.34 mg/m³.

MSHA:

Mine Safety and Health Administration. In all American mines, MSHA is the safety and health regulator, similar to the Ministry of Labour (or equivalent) in Canadian provinces.

Nylon cyclone (10-mm):

Part of a respirable dust sampling train (defined below) which removes the large, non-respirable dust particles from the airborne dust sample when the sampling flow rate is set at 1.7 litres per minute (L/min).

Opacity:

The extent to which a medium is opaque and able to block the transmission of light.

Organic carbon (OC):

The complex carbon compounds found in diesel particulate, including hydrocarbons such as aldehydes and polycyclic aromatic hydrocarbons (PAHs). Organic carbons do not include elemental carbon and inorganic substances such as sulphates.

Pre-separator:

In a sampling train, the pre-separator removes a portion of the airborne dust that does not need to be collected. In the case of respirable dust, a 10-mm nylon cyclone used as pre-separator removes the larger, non-respirable dust.

Respirable dust:

Dust small enough to penetrate deep into the lung. Respirable dust is sampled using a 10-mm nylon cyclone (defined above) used as a pre-separator in the sampling train. The sample flow rate is set at 1.7 L/min. The dust sampled this way has a median size of 4 micron.

Respirable combustible dust (RCD):

The portion of a respirable dust sample that can be burned off a silver membrane filter when exposed to a temperature of 400°C for two hours. In most Canadian provinces, RCD has been used as a measure of the exposure of miners to diesel particulate matter.

Sampling train (dust):

The complete assembly of what is required to perform dust sampling. It includes: a self-regulated pump, plastic/rubber tubing, lapel clips and a filtration medium in a sampling cassette to collect the dust sample. It may or may not include a pre-separator. In the case of respirable dust sampling, a nylon cyclone is used as a pre-separator to remove the coarse, non-respirable dust.

Steady-state conditions (diesel engines):

Mode of operation of a diesel engine where conditions are stable. This includes constant speed and load and ideally, stabilized exhaust temperatures and pressures as well. An engine operating continuously at full throttle while the transmission is in neutral would be an example of an engine operating in a steady-state condition.

Thermogram:

The graphical summary of the analysis from the software used in the NIOSH 5040 method for carbon analysis. This graph shows the relative amounts of elemental and organic carbon and analytical conditions including oven temperature and time settings.

Torque converter stall (full - diesel engines):

A steady-state engine/vehicle operating condition where the vehicle is in high gear, the brakes are applied and the throttle is fully depressed. This is the preferred test condition to determine the state of maintenance of an engine, whether using particulate sampling or toxic gas measurement. **Note: this test is conducted under heavy static load and should only be performed by a qualified, trained person. In addition, torque converter fluid temperature has to be monitored for overheating. More than 60 seconds in this mode of operation can result in serious damage to the torque converter. This test cannot be performed on vehicles with manual transmissions.**

Total carbon (TC):

The combination of organic and elemental carbon found in diesel emissions. This excludes inorganic substances such as sulphates and usually makes up about 85% of diesel particulate matter.

Background

Whether on highways or underground, everyone has seen the smoky black exhaust that is emitted by diesel engines. The incomplete combustion of diesel fuel results in the formation of solid and liquid particles in the exhaust. This black soot is made up of hundreds of individual compounds, several of which are known ***carcinogens***.

Figure 1 is a schematic drawing showing some of the individual components of ***diesel particulate matter (DPM)***. The basic building blocks are very small solid carbon particles that are less than 0.1 ***micron*** in diameter (1). These particles in turn attract and ***adsorb*** several types of hydrocarbons and also serve as a carrier for the condensed liquid hydrocarbons. Sulphates can also be found on the carbon particles depending on the fuel sulphur content.

All of this material is DPM, and if a perfect sampling and analysis method existed, it would be possible to sample all of DPM and only DPM. Unfortunately, this is not the case. Samples of diesel exhaust usually include other particles found in the work environment. Their presence can cause the samples to over- or under-estimate exposure to DPM.

One very important physical characteristic of DPM is its size. DPM is a sub-micron aerosol (see Figure 1). As such, it is ***respirable dust***, and it is more likely to penetrate the deepest part of the lung, where oxygen enters the blood stream. This causes concerns, because in this region of the lung, the body has fewer means of removing hazardous particles which attach to the lung tissue.

Another consequence of the small size means that DPM is not easily removed from the air stream. Unlike mineral dust, it will not settle to the ground easily under the action of gravity. Once it is airborne, a portion of DPM will likely remain airborne all the way to the mine exhaust. This means that DPM not only affects the work place where it is produced, it also contaminates workplaces downwind. This is why control of DPM at the source is so important.

Health Concerns, Exposure Limits and Guidelines

Problems associated with diesel contaminants in the workplace include irritation of the eyes and throat. In addition, large amounts of diesel exhaust can affect the vision of vehicle operators and can be a safety hazard in an environment where visibility is already compromised by the size of the equipment and darkness.

Some of the compounds found in DPM are known carcinogens. Because of that, it is possible that DPM as a whole can be a carcinogen at some level of exposure.

Mines have higher than average occupational exposure levels to DPM (1), which is why the mining community is currently involved in research aimed at controlling DPM in the workplace.

As early as 1988 the National Institute for Occupational Safety and Health (NIOSH) issued a report which stated that diesel exhaust as a whole is a suspected occupational carcinogen (2). Very recently, the U.S Environmental Protection Agency (EPA) classified diesel exhaust as "likely to be carcinogenic" (3). In 1990 the Canadian ad hoc Diesel Committee published a guideline suggesting that exposure to DPM should be measured using the ***Respirable Combustible Dust*** or ***RCD*** method and be limited to 1.5 ***mg/m³*** over a normal 8-hour shift (4). This exposure value has since been adopted by most mining provinces in Canada.

In January 2001, the Mine Safety and Health Administration (MSHA) issued a final ruling for U.S. metal and non-metal mines (5). In this ruling, MSHA requires that mines meet a limit of exposure 0.40 mg/m³, 18 months after acceptance of the tabled document. Mines would then be expected to reduce exposure in order to meet a 0.16 mg/m³ limit of exposure by January 19th, 2006. This limit of exposure is based on the measurement of ***total carbon*** using the NIOSH 5040 method described in this report.

Agency/Committee/Regulator	Date Submitted	Exposure Guideline/Limit	Substance Measured
Canadian ad hoc Diesel Committee (presently in effect in most Canadian mining provinces)	1990	1.50 mg/m^3	*RCD*
Mine Safety and Health Administration	2001	0.40 – 0.16 mg/m^3	*TC*
Switzerland, tunnelling	N/A	0.20 mg/m^3	*TC*
American Conf. of Gov. Industrial Hygienists	1996	0.15 mg/m^3	*TC*
American Conf. of Gov. Industrial Hygienists	1998	0.05 mg/m^3	*TC*
Germany, tunnelling	N/A	0.10 mg/m^3	*EC*
American Conf. of Gov. Industrial Hygienists	2001	0.02 mg/m^3	*EC*

Table 1. Proposed/adopted exposure limits and guidelines.

The American Conference of Governmental Industrial Hygienists (ACGIH) is the organization that publishes the Threshold Limit Value (TLV®) guidelines on an annual basis. The ACGIH guidelines are not regulated limits by themselves but are used in many parts of the world as legal exposure limits by regulators. In 1996, the ACGIH published a notice of intended change in which a DPM TLV® of 0.15 mg/m^3 was suggested (6). In 1998 the ACGIH further reduced this proposed TLV® to 0.05 mg/m^3 (7). Both of these limits were based on the measurement of total carbon similar to the MSHA rule. In 2001, the ACGIH suggested a limit of 0.02 mg/m^3 based on the measurement of ***elemental carbon*** only (8). Elemental carbon is also measured using the NIOSH 5040 method. These guidelines and/or limits are summarized in Table 1.

European mines and tunnel construction projects are also subjected to DPM limits of exposure. In Europe, a method similar to the NIOSH method is used to measure elemental and ***organic carbon***. Countries have adopted different limits of exposure depending on whether elemental or total carbon is measured for compliance purposes. In German tunnelling, for example, elemental carbon is used as a measure of exposure to DPM and it is limited to 0.10 mg/m^3. In Switzerland tunnels, the limit of exposure is 0.2 mg/m^3 and total carbon is used as a measure of exposure to DPM.

Sampling for DPM in Mines

There are many reasons why mine operators sample for DPM. Most samples are taken for compliance purposes, in other words, to show that exposure of workers is below the allowable regulated limit. But there are several other reasons to sample mine air or engine exhaust for DPM concentration. Sampling can help verify the state of maintenance of an engine, measure the efficiency of a particulate filter or other exhaust treatment devices or monitor the efficiency of a local ventilation network. In this section several techniques that can be used to monitor DPM will be described.

Personal exposure monitoring is the type of sampling that is most commonly performed. In Canada, personal sampling for DPM has been regulated for about 10 years in several mining provinces. Important sampling strategies will be discussed in order to get the most out of exposure data monitoring. Sampling protocols in Canada and the U.S. will be described in general.

In addition, raw exhaust sampling of DPM and gases will be described, based mostly on the DEEP experience from the field studies that were funded through this consortium. Equipment and procedures to test the DPM filtration efficiency of after-treatment modules (e.g. ceramic filters) and to evaluate the impact of

diesel equipment maintenance on gaseous and particulate emissions will also be described.

Personal Sampling

Sampling Strategy – Diesel Particulate

The diesel sampling strategy for personal exposure monitoring must address the selection of workers (based on duties and work locations), the sampling period during the work shift, the number of workers to be sampled and the frequency of sampling.

Ideally, all workers exposed to diesel particulate matter should be sampled. In most workplaces, however, comprehensive sampling of all workers is nearly impossible because of the amount of time required and the cost involved. A more flexible strategy can be used, including:

- The sampling of higher risk employees. For diesel particulate these would include diesel equipment operators, mechanics or any other workers whose duties take place in an environment where diesel vehicles are used routinely. Because the amount of exposure to diesel can vary considerably and it is not always possible to know which workers are exposed the most, it is important to sample as many of the high risk workers as possible.

- The separation of employees into occupational groups, or groups of employees who due to the nature of their work or work location are likely to be exposed to similar amounts of diesel particulate matter. Workers are then selected randomly and their exposure is monitored. There are guidelines governing the number of samples to be taken and the frequency of sampling (9,10). These guidelines include more frequent sampling if the group's average exposure is high or if there is a lot of variability in the results. Other factors include random and appropriate selection of the sampling days to take normal productions and maintenance cycles into account. Shift work and seasonal effects can also have an impact, so sampling in a random fashion throughout the year is important. For smaller occupational groups (less than 10 employees), all employees should eventually be sampled.

Reporting and use of exposure data should be considered as the most important step in the procedure. The following items should be kept in mind:

- Results of analysis and exposures should be compiled in straightforward documents, using tables and terminology that can easily be understood.

- Abbreviations/technical terms must be explained and non-relevant information should be excluded in order to enhance clarity.

- Clearly highlight high or non-compliant exposure levels.

- Organize data in logical categories such as by date, substance, work activity, mine location or other relevant characteristics. This will help pinpoint problem processes or areas and will facilitate the implementation of corrective actions.

- Always act upon high exposure samples. This can include re-sampling or the application of corrective actions.

- Apply controls at the source as opposed to generalized controls such as increasing ventilation to a given workplace or area. This is expensive and does not always protect everyone.

Collecting Personal Samples

Personal sampling is usually performed to measure the exposure of individual workers or for assessing compliance with regulated exposure limits. Some of the procedures are summarized below, but more details can be found in reference 11. Some differences in the ***sampling train*** components, the assembly and the sampling flow rate exist depending on the method used (RCD or MSHA regulation). Also, the requirements for sampling the worker directly or the general area where he/she works may vary depending of the jurisdiction. Regulations should be consulted in order to ensure compliant sampling and analysis.

RCD Method (Canada)

In this case, the sampling train consists of a cyclone, the filter cassette, a length of tubing, lapel clips and a constant flow sampling pump. The ***pre-separator*** is a 10-mm nylon cyclone which removes the coarse (non-respirable) portion of the airborne dust. It should be cleaned prior to each use and checked for obstructions or manufacturing defects. Since this is a respirable dust sample, the pump flow has to be set to 1.7 litres per minute (L/min). The sampling train fitted on a worker is shown in Figure 2.

MSHA Regulation (United States)

For sampling according to the MSHA final ruling for metal and non-metal mines, the sampling train consists of all the components listed above for the RCD method. An additional component, an ***impactor***, is inserted between the cyclone and the filter cassette. Its purpose is to remove the respirable dust particles larger than 0.9 micron in size. This prevents larger, non-diesel dust particles from being sampled and analyzed as diesel particulate. The flow rate required in this case is 1.7 L/min. MSHA requires that the NIOSH 5040 analytical method be used to determine the amount of total carbon on the sample as an indication of exposure to DPM.

Good Sampling Practice Common to Both Methods

Regardless of the method used to analyze the sample, sample collection should take the following into account:

- The pump must be electronically controlled and self-regulated, with sufficient battery capacity to last an entire shift while under load (with a filter in line). It should be intrinsically safe if used in a potentially explosive atmosphere and the pump case should be made of a material that shields the pump controls from ***electro-magnetic fields***. If the pumps are used close to large electrical motors, rapid changes in these fields on motor start-up or shut-down could stop the pump or affect the sampling flow rate.

- The pump flow rate is adjusted using a calibrated electronic flow calibrator or a soap bubble burette of at least one litre capacity.

- The pump flow has to be checked prior to sampling and should be checked after sampling to ensure that the flow was maintained through the shift. The pump flow should remain within a 5% range during the entire sampling period.

- Sampling <u>should</u> be conducted "collar to collar", that is, for the entire duration of the shift. This is the only direct way to compare total shift exposure to a regulated exposure limit.

- The type of filter used depends on the DPM analytical method used. The next section specifies the type of filter required for each method.

- It is recommended that the analytical laboratory or an approved supplier/manufacturer provide the sampling cassettes/filters to the responsible person at the mine site. Loading and preparation of the sampling cassette at the mine site is not recommended for reasons of quality control and uniformity.

- Care should be used when assembling the sampling train. When attaching the cassette to the cyclone make sure that the cassette inlet is fitted to the cyclone outlet. There can be confusion with the RCD sampling train, where it is possible to fit the filter cassette backwards.

- The tubing connecting the filter cassette to the sampling pump must be long enough to ensure a comfortable fit on the worker. If the tubing is re-used, the ends should be checked and cut if necessary to produce a tight fit to the pump and filter cassette ends.

- Placement of the pump on the worker should take into account the work being done. It can be placed on the worker's belt on the side opposite the lamp battery and slightly towards the back. For equipment operators, it can be shifted to the side. In any case the tubing should be secured to the worker's clothing to ensure that it will not get in his/her way and that it will not be pinched during the shift.

- The cyclone must be placed in the worker's breathing zone (the lapel is a good place) and the cyclone inlet opening has to be aimed away from the worker to ensure that it will be unobstructed throughout the shift. Ensure that oilers or overcoats (winter) do not cover and restrict the cyclone opening.

- Blank filters from each batch of filters should be kept as ***field blanks*** and sent back to the laboratory for analysis. This is a quality control step which could help identify problems in procedure or handling.

Personal Sample Analysis

After a dust sample is collected, it should be sent to an accredited laboratory for analysis. Diesel particulate matter is a complex mixture of several chemical components. As a result, DPM is very difficult to accurately analyze directly because ***interference*** from other substances commonly found in the workplace can affect the analysis. All of the techniques available today can potentially be affected by interference. A good example is drill oil mist that could be measured as DPM depending on which analytical method is used and how the resulting data are interpreted.

There are presently two main analytical methods that can be used to measure workers' exposure to DPM. The first one, the Respirable Combustible Dust (RCD) method is used in most Canadian provincial regulation. The other is the NIOSH 5040 method, which measures elemental carbon, organic carbon and total carbon.

Respirable Combustible Dust (RCD) Analysis

Diesel particulate can be ashed (burned) from the sample filter if it is placed in a furnace at a temperature of 400°C for a minimum period of two hours. This requires that a silver membrane filter be used for the sampling process. Silver acts as a catalyst, which enables the DPM to be burned at a lower temperature. Weighing of the filter before and after ashing yields the mass of dust burned off in the process (RCD). This value is used as an estimate of the DPM mass collected on the filter. The concentration is calculated using this mass, the sampling flow rate and the total sampling time. More information on the RCD method is available elsewhere (12, 13, 14).

Filter: Silver membrane filter, 25 mm diameter, 0.8 μm pore size.

Advantages: This is a simple and inexpensive method. Since it is performed on a silver membrane filter, the sample can also be analyzed for respirable quartz (silica) dust. This method is the one used in most mining regulation in Canada and because of this, analytical services are available from several laboratories.

Disadvantage: Some mineral dusts could cause this method to underestimate the amount of diesel particulate in the sample. Mines with high sulphide orebodies or that make use of high sulphur content fuel could experience this type of problem. Drill oil mists, cigarette smoke or other sources of carbon could cause this method to overestimate the exposure to DPM. Because weighing is involved, this method is not as accurate or precise as the NIOSH 5040 method (see below). In the future as exposure limits and concentrations of diesel particulate in mine air are reduced the RCD method may no longer be an alternative.

NIOSH 5040 Method – Carbon Analysis

The analysis for this method is more complicated than that of the RCD method. In the analytical instrument, the temperature and the analytical cell atmosphere are controlled to measure elemental carbon and organic carbon independently. Laser light is used to measure light transmittance through the filter in order to

precisely determine the proportions of elemental and organic carbon. The carbon dioxide which is produced during the controlled "burn" of the dust sample is measured and the mass of elemental and organic carbon deduced. Again, the sample flow rate and the sampling time are used to calculate the airborne concentration of diesel particulate. The instrumentation and a typical ***thermogram*** are shown in Figures 3. More information on the NIOSH 5040 method is available elsewhere (15, 16).

Filter: Quartz fibre filter, 37 mm diameter

Advantages: This method is more precise and accurate than the RCD method. There is still some discussion as to which component (organic carbon, elemental carbon or both) of the analysis should be used to be the measure of exposure to DPM. Although elemental carbon is only part of the airborne diesel particulate, it is probably the best marker or indicator of exposure to DPM. Selection of an exposure limit value based on elemental carbon is likely to be the best approach. If this is done, the chances of overestimating exposure because of the presence of organic substances from other sources will be significantly reduced .

Disadvantages: At this time, the NIOSH 5040 method is not widely used. Since it is not specified in Canadian mining regulation, only a few instruments are presently available in Canada and in the United States. As the new MSHA ruling is applied, demand for the analytical process will likely increase and more laboratories will come on line. This should ensure that the services are widely available and priced accordingly. The final MSHA ruling for metal and non-metal mines (5), requires an additional component in the sampling train in order to eliminate dust and particles larger than 0.9 micron in diameter. This component is a disposable impactor and it is recommended for use in mines where specific types of dusts can cause interference problems. The presence of this impactor reduces, but does not completely eliminate the potential for other carbon based compounds to interfere with the analysis.

DEEP Research on Sampling and Analytical Methods

The Diesel Emissions Evaluation Program (DEEP) has committed a large amount of resources to field testing of the two methods described above. The reports from these studies are listed in the reference section (17, 18, 19). They can be found in full on the DEEP Web Site at www.deep.org .

In summary, these studies have found that when tested in the field on a side by side basis both the RCD and the NIOSH 5040 method agree very well as long as airborne concentrations of diesel particulate matter are high enough. Results show that for regulated exposure limits to diesel particulate matter less than 0.6

mg/m3, the NIOSH 5040 method or a similar analytical approach could be the only available alternative.

Direct Exhaust Sampling

Sampling of DPM directly in the engine exhaust is not done routinely in mining mainly because it is not a regulated requirement in Canada or in the United States. In addition, this type of sampling involves complex equipment and procedures. Tailpipe measurements of DPM and gaseous emissions are good tools to assess the state of health of an engine, the need for maintenance and is also the best way to determine the impact of exhaust cleaning equipment (e.g. high efficiency filters).

Direct exhaust sampling of DPM usually requires that the engine test be conducted under ***steady-state conditions***. The recommended steady-state engine regime for direct exhaust testing is full throttle while under ***torque converter stall***. This section describes instrumentation and several applications of direct exhaust sampling.

Testing the Efficiency of DPM Reduction Technology

In this application, the efficiency of a diesel particulate filter (DPF) such as a ceramic filter or any other technology that can potentially reduce exhaust particulate, is measured. While the engine is in a steady-state mode of operation, the amount of diesel particulate is measured in the exhaust pipe, upstream and downstream of the DPF. The reduction in diesel particulate concentration due to the DPF is the measure of its filtration efficiency.

One instrument was designed specifically to do this type of efficiency measurement for diesel filters. It is the Nanomet manufactured by Matter Engineering in Switzerland. The instrument shown in Figure 4 performs an indirect measurement of elemental carbon upstream and downstream of the DPF while the engine is operating. It includes a heated dilution sampling head which is the preferred approach when sampling directly in the exhaust stream. Although the instrument was designed for use in the field, tests underground have shown that it is sensitive to use in rugged environments and requires a significant amount of training and experience to be operated proficiently. This instrument is being used in the evaluation of high efficiency DPF in tests presently underway at Brunswick Mine as part of the DEEP research program. Additional information on this project can be found on the DEEP Web Site (www.deep.org).

Sampling for DPM in Undiluted Exhaust

Direct sampling of DPM in exhaust can also be used to assess the impact of maintenance on diesel engines. Problems such as dirty intake air filters or high exhaust back pressure can lead to very high levels of diesel particulate in the exhaust. To this end, an undiluted sampling package has been designed by CANMET for use in the DEEP Maintenance project (20) which took place at Falconbridge's Strathcona Mine. Since the acquired sample is not diluted, care has to be taken to cool the sample to below 50°C and keep condensation under control in the sampling line.

Measurement of the DPM concentration in the exhaust, before and after maintenance procedures, gives a measurement of the impact of the specific maintenance action. The final report of investigation for the maintenance project can also be found on the DEEP Web Site.

Sampling of Undiluted Exhaust Gases - UGAS

The Undiluted Gas Analysis System$_{Patent}$ (UGAS) was developed by the Noranda Technology Centre (NTC) to assist in the maintenance of diesel engines and the measurement of exhaust emissions. This system was also used for measuring the effects of maintenance on emissions for the DEEP Maintenance Project. The system incorporates an ECOM AC electronic gas analyzer. The ECOM analyzer uses electro-chemical cells to monitor toxic exhaust gases such as CO, NO and NO_2. It also has sensors for temperature and pressure measurement. The analyzer is capable of communicating diagnostic data to a computer if the data needs to be stored.

The UGAS software controls the ECOM analyzer. It uses a built-in testing protocol which guides the diesel mechanics through the sampling process. This way, the tests are repeatable and accurate. This allows an engine's state of maintenance to be followed as a function of time or different engines of the same type or model to be compared. The gas analyzer, personal computer and related hardware are all assembled in an industrial enclosure on wheels capable of being rolled to a vehicle for engine and emissions diagnostics (Figure 5 and 6).

At present, the UGAS software is the sole property of the Noranda group but it should be available on the market very soon. Other direct exhaust gas samplers are available, but these were not used in DEEP research projects. These and the ECOM analyzer cannot measure diesel particulate matter directly.

Measurement of Carbon Monoxide in Undiluted Exhaust

Except for the ECOM/UGAS tests described above, direct sampling of carbon monoxide concentration in exhaust was not performed in any of the DEEP supported studies. However, this method of checking the state of maintenance of diesel engines is used widely in Canada and in the United States by the mining industry. Mine regulations require that exhaust concentrations of CO not exceed a certain value (21) or alternatively that the vehicle receive maintenance if the baseline value concentration (when the new vehicle is first delivered to the mine site) doubles (22). Sampling for CO in the exhaust is best performed under a loaded duty cycle (torque converter stall), but this is not possible for the entire underground fleet since manual transmission vehicles cannot be tested safely or effectively while stationary and under load.

Real time CO monitors and gas testing tubes (Figure 7) can be used to perform these tests and there are advantages and disadvantages to both approaches. In both cases, cooling tubes must be used ahead of the samplers. More information on the testing procedure can be found elsewhere (23).

Some of the things to remember while performing the tests include:

- Take every precaution in order to protect the person performing the tests from the vehicle emissions, the exhaust heat and physical harm from sudden vehicle movement.

- If using gas tubes, make sure that the hand pump bellows is sound (not punctured) by compressing the hand pump, inserting an unopened tube and checking that the vacuum inside the pump is maintained for 10 minutes.

- If using direct reading electronic gas monitors, make sure these are calibrated on a routine basis according to the manufacturer's recommendations.

- Let the engine come to a stable operating temperature. Once the duty cycle has begun, wait at least 15 seconds before starting the sampling procedure. The CO concentration will likely drop and stabilize after that period of time. This is easy to see when using a direct reading instrument, but not with a gas monitoring tube.

Opacity Measurement

Opacity meters, also known as smoke meters are used to measure diesel smoke opacity (particles suspended in the exhaust) in the tailpipe. These instruments do

not accurately measure DPM concentrations, but are a quick and easy-to-use tool to evaluate the condition of an engine or gross malfunctions of DPM control technologies such as ceramic or other high efficiency filtration units.

Two types of smoke meters are commercially available, a full-flow type or a sampling type. The full–flow type smoke meters are clamped onto the diesel equipment tailpipe and measure the opacity across the entire exhaust gas stream. The reading from this type of smoke meters can be affected by ambient conditions, such as wind, humidity and bright light. The sampling type smoke meters draw a portion of exhaust gas into a measurement chamber. The smoke sample has to fill this chamber quickly and completely before the measurement can begin. For both types of smoke meters, a beam of light travels through the sample medium and the signal is processed by a photocell receiver on the other end. An opacity reading is then calculated. Opacity is the portion of the light which is prevented from reaching a light detector because of the presence of suspended particulate. The opacity can vary from 0% in a clean exhaust stream to 100% if no light is transmitted because of heavy particulate concentration.

Conclusion

Exposure monitoring for DPM in mines is likely to see significant changes in the near future. Limits of exposure will no doubt be reviewed as well as sampling and analytical methods. The importance of personal sampling at this time cannot be overstated. Sound knowledge of the available procedures and good exposure database management is a must.

In addition, there are options, tools and procedures available to the industry for direct exhaust sampling. These can help determine the impact of diesel exhaust treatment technology and state of maintenance of diesel engines in order to enhance the mine workplace environment.

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Appendix I – Figures

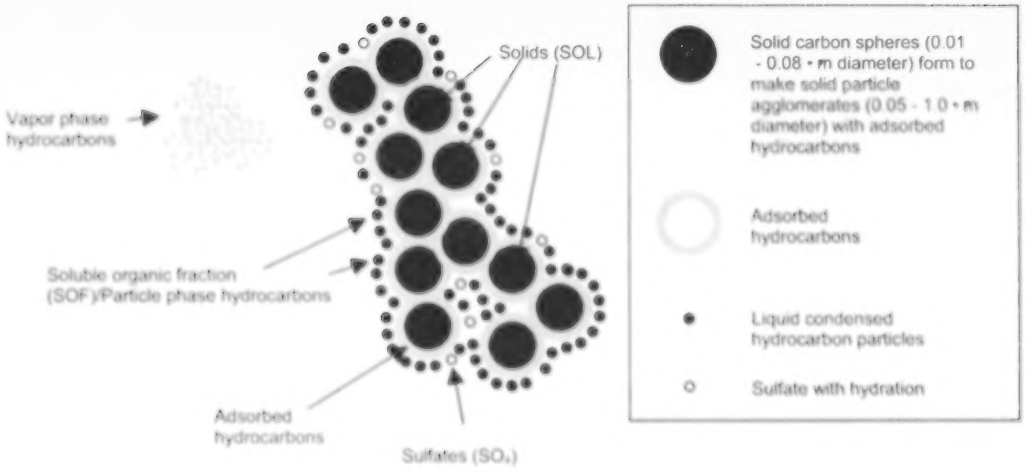
Vapor phase hydrocarbons
Solids (SOL)
Soluble organic fraction (SOF)/Particle phase hydrocarbons
Adsorbed hydrocarbons
Sulfates (SO_4)
Solid carbon spheres (0.01 - 0.08 • m diameter) form to make solid particle agglomerates (0.05 - 1.0 • m diameter) with adsorbed hydrocarbons
Adsorbed hydrocarbons
Liquid condensed hydrocarbon particles
Sulfate with hydration

Figure 1. Diesel particulate matter (reproduced from Reference 1)

Figure 2. Dust sampling train

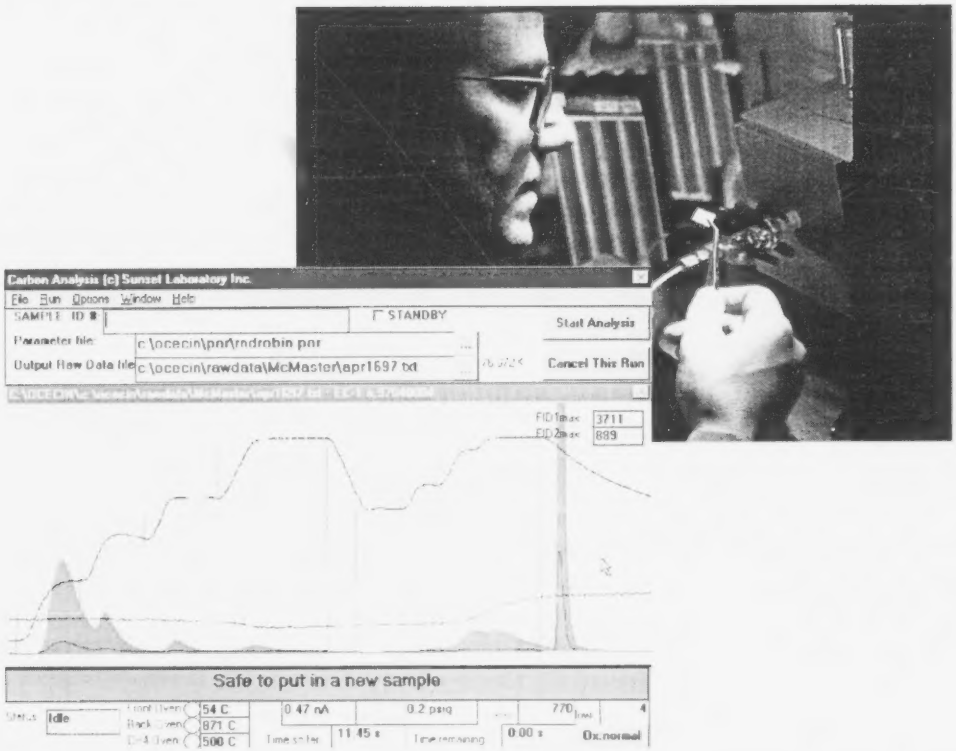

Figure 3. NIOSH 5040 Method - thermogram

Figure 4. Nanomet instrument

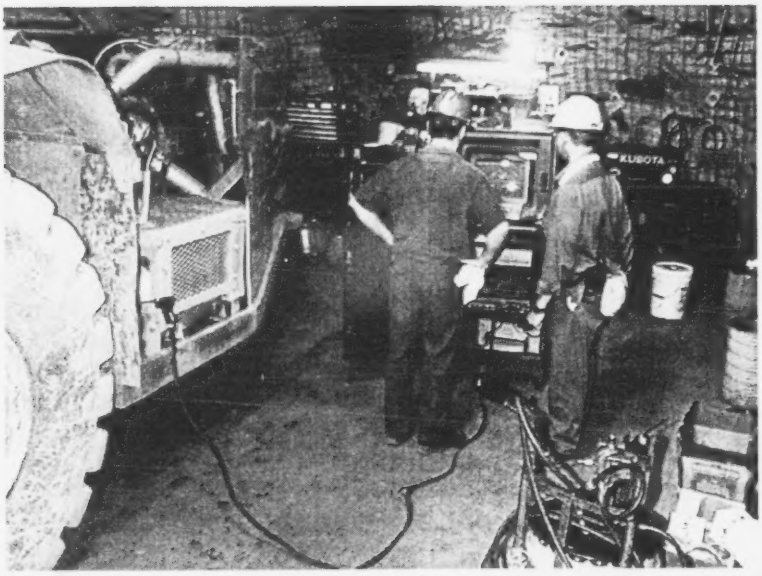

Figure 5. UGAS/ECOM direct exhaust sampling

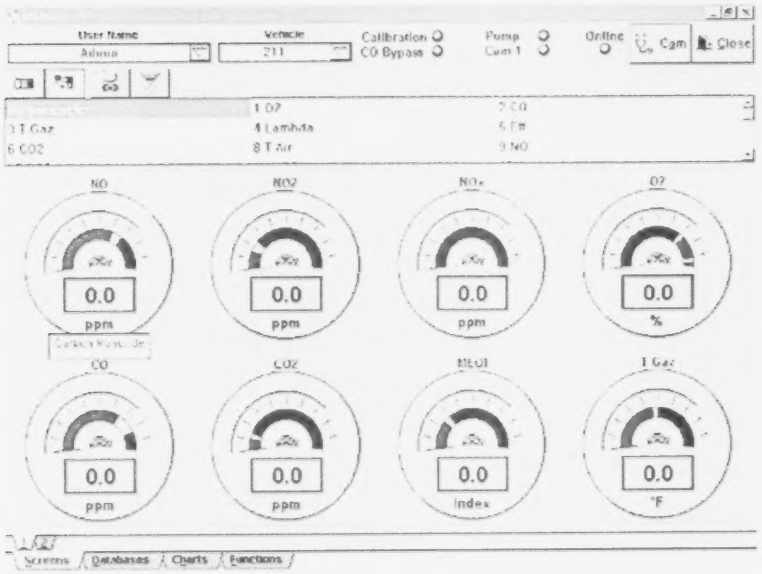

Figure 6. UGAS software control panel

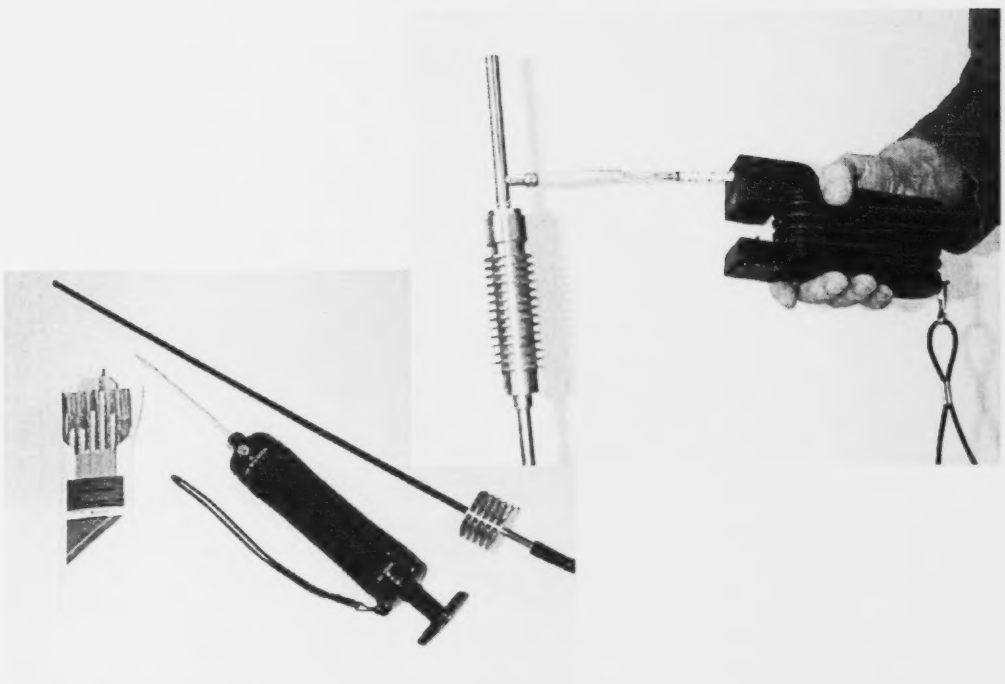

Figure 7. Carbon monoxide sampling using gas tubes